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SELECTING VERY SOFT X-RAY SOURCES IN EXTERNAL GALAXIES: LUMINOUS SUPERSOFT X-RAY SOURCES AND QUASISOFT SOURCES

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ABSTRACT

We introduce a procedure to identify very soft X-ray sources (VSSs) in external galaxies. Our immediate goal was to formulate a systematic procedure to identify luminous supersoft X-ray sources (SSSs), so as to allow comparisons among galaxies and to study environmental effects. The focus of this paper is on the design of the selection algorithm and on its application to simulated data. In the companion paper we test it by applying it to sources discovered through *Chandra* observations of 4 galaxies. We find that, in its application to both simulated and real data, our procedure also selects somewhat harder sources, which we call quasisoft. Whereas values of kT for SSSs are typically tens of eV, some quasisoft sources (QSSs) may have kT as high as $\sim 250-300$ eV. The dominant spectral component of other QSSs may be as soft as SSS spectra, but the spectra may also include a low-luminosity harder component. We sketch physical models for both supersoft and quasisoft sources. Some SSSs are likely to be accreting white dwarfs; some of these may be progenitors of Type Ia supernovae. Most QSSs may be too hot to be white dwarfs. They, together with a subset of SSSs, may be neutron stars or, perhaps most likely, accreting intermediate-mass black holes.

Subject headings: methods: data analysis — X-rays: binaries — X-rays: galaxies

1. INTRODUCTION

1.1. *Goals*

First identified as a class of X-ray sources approximately 11 years ago, luminous supersoft X-ray sources (SSSs) were characterized by kT on the order of tens of eV, and L in the range $10^{37}-10^{38}$ erg s^{-1}.[1] Because radiation from SSSs is readily absorbed by the interstellar medium (ISM), we can study large numbers of them only by searching for them in external galaxies. The spatial resolution of *Chandra*, and of *XMM-Newton* as well, make such studies possible. The great distances to other large galaxies means, however, that the count rates of most of the SSSs we can detect in them are low. Spectral fits are therefore possible for only a small fraction. The primary goal of the work described in this paper is to provide a well-defined and systematic method to select, from a set of X-ray sources dominated by low-count sources, good SSS candidates. In its present form, the procedure works well for both *Chandra* and *XMM* data.

1.2. *SSSs in Galaxies*

Soft X-ray sources, including the flagship SSS binaries CAL 83 and CAL 87, had been discovered during a survey of the Magellanic Clouds conducted with the *Einstein* X-ray observatory (Long, Helfand, & Grabelsky 1981; Seward & Mitchell 1981). The large-scale study of SSSs in other galaxies began with *ROSAT* observations of ~ 30 SSSs in the Magellanic Clouds, and in M31. Because M31 is similar in many ways to other large spiral galaxies, it may be a good guide to the sizes of galactic populations of SSSs. *ROSAT* detected ~ 15 SSSs with luminosities greater than $\sim 10^{37}$ erg s^{-1} in M31[2]. These observations, combined with simple models for galactic gas distributions, led to an estimate that, at any given time, M31 houses ~ 1000 active SSSs (Di Stefano & Rappaport 1994). A similar analysis of the sources and gas distribution of the Milky Way found that its population of SSSs could be comparably large.

The subsequent discovery of the low-luminosity extension ($10^{35}-10^{36}$ ergs s^{-1}) of the class (Greiner et al.1999, Greiner & Di Stefano1999, Patterson et al. 1998) may imply that the Milky Way's population of SSSs is at least an order of magnitude larger. Recent *Chandra* studies (Di Stefano 2002, 2003) find convincing evidence of a lower-luminosity component of the class of SSSs in M31 as well. If these estimates are correct, and if our Galaxy and M31 are typical, SSSs may form the single largest galactic population of luminous ($L_X > 10^{35}$ erg s^{-1}) X-ray binaries. Whatever their fundamental natures, the likely large sizes of SSSs populations indicates that they may be pumping $10^{40}-10^{41}$ ergs s^{-1} of highly ionizing radiation into the ISM of their host galaxies.

1.3. *From Supersoft Sources to Quasisoft Sources*

In the absence of a single definitive model for SSSs, and with only a small number of known SSSs in the Galaxy and Magellanic Clouds, we did not want to eliminate sources that were somewhat harder than the canonical sources such as CAL 83. For reasons summarized in §2 and in §3.1, we therefore chose a cut-off in kT of 175 eV for SSSs. We found, however, that the methods we devised to select sources up to any given temperature, inevitably also included sources that either have (1) somewhat higher temperatures, but generally in the range $175-250$ eV, or (2) SSS-like spectra, but with some harder emission as well.

[1] See e.g., RX J0019.8+2156: Reinsch, Beuermann, & Thomas 1993, Beuermann et al. 1995; RX J0925.7-4758: Motch, Hasinger, & Pietsch 1994; GQ Mus: Ogelman et al. 1993; 1E 1339.8+2837: Hertz, Grindlay, & Bailyn 1993; AG Dra: Greiner et al. 1996; RR Tel: Jordan, Mürset, & Werner 1994; 1E 0035.4-7230: Seward & Mitchell 1981; RX J0048.4-7332: Kahabka, Pietsch, & Hasinger 1994; RX J0058.6-7146: Kahabka et al. 1994; 1E 0056.8-7154: Wang 1991; RX J0513.9-6951: Schaeidt, Hasinger, & Trümper 1993; CAL 83: Long, Helfand, & Grabelsky 1981; CAL 87: Long et al. 1981; RX J0550.0-7151: Cowley et al. 1993.

[2] Subsequent reanalysis of the *ROSAT* data identified additional SSS candidates, bringing the number to 34 (Kahabka 1999)

This suggests two possible results for the method's application to real data. First, if there are few or no soft sources just slightly harder than the canonical SSSs, the procedure will select only SSSs. Second, if there is a supply of somewhat harder sources, we will select them as well. We have now had opportunities to apply the selection criteria to the 4 galaxies studied in the companion paper (Di Stefano & Kong 2003), to M104 (Di Stefano et al. 2003a), M31 (Di Stefano et al. 2003b), and roughly one dozen additional galaxies (Di Stefano et al. 2003c). We have found that most galaxies have significant populations of both SSSs and sources with somewhat harder spectra (e.g., $kT < 250$ eV). We refer to the latter as quasisoft sources (QSSs).

Our selection procedure distinguishes between SSSs and QSSs according to which step in the algorithm identifies the source as being very soft. In the galaxies we have studied, spectral fits for the brightest SSS and QSS candidates have verified that the algorithmic classification works. To simplify the terminology, we will sometimes use the term "very soft source" (VSS) to refer to both SSSs and QSSs.

1.3.1. *Quasisoft Sources*

The physical significance of this new class is not yet understood, but there are likely to be several physical models corresponding to QSSs. First, hot SSSs located behind large gas columns will have photons in the medium energy band, M ($1.1-2$ keV), but may have few photons in the soft band, S ($0.1-1.1$ keV). For such sources, the hardness ratios typically used to identify SSSs will have values not normally associated with SSSs, even though their intrinsic characteristics clearly place them in the SSS category. Second if the detector has poorer than anticipated sensitivity to soft photons, soft sources can appear to be harder than they actually are. Thus, some QSSs are likely to have the same physical characteristics as some other sources identified as SSSs. Finally, some QSSs are likely to be genuinely harder than SSSs, so hard that white dwarf models can be ruled out. As we will discuss in §2, intermediate mass black hole models may be appropriate for such systems, but neutron star or stellar mass black hole models should also be considered.

1.4. *Open Questions*

Below we list some of the questions we hope to answer with studies that compare VSS populations in different galaxies.
(1) What are typical galactic populations of SSSs and QSSs? Irrespective of their fundamental natures, the answer to this question will allow us to estimate the influence of soft X-ray sources as ionizers of the ISM.
(2) Are any spiral galaxy parameters related to the relative sizes of SSS and QSS populations? Answering this question can provide insight into the age of the populations that spawn very soft sources, and hence might help to illuminate their nature. Di Stefano & Rappaport (1994) suggested that for spiral galaxies, the size of the SSS population might scale with blue luminosity, but this has not been tested.
(3) Do elliptical galaxies house large SSS/QSS populations? Although it has been suggested that the diffuse soft emission in ellipticals may be due to SSSs (see, e.g., Fabbiano, Kim, & Trinchieri 1994), we still know very little about SSSs in ellipticals. If accreting WDs form the largest segment of SSS populations, and if a significant fraction of the donor stars have masses small enough to be typical of the stars found in elliptical galaxies, then we may expect SSSs to be important parts of the X-ray source population in ellipticals.
(4) Within spiral galaxies, what are the relative populations of SSSs/QSSs in the galaxy bulges and disks?
(5) Do galaxies with massive central black holes have more SSSs or QSSs located within 1 kpc of the nucleus than comparable galaxies without massive central black holes? It has been suggested that some SSSs within the central kpc of galaxies which harbor massive black holes may actually be the stripped cores of stars that have been tidally disrupted (Di Stefano et al. 2001). Verification of this hypothesis by studying individual SSSs will be difficult, so statistical studies of SSS populations in a large number of galaxies may provide the best tests.
(6) For all galaxies, are the positions of QSSs and SSSs correlated to the positions of other objects, such as HII regions, planetary nebulae, supernova remnants, or globular clusters? The distances to most external galaxies are too large to allow for convincing optical identifications. It is nevertheless useful to identify the types of populations which tend to be associated with VSSs. This can provide clues to their fundamental natures.
(7) Are SSSs significant contributors to the rates of Type Ia SNe? The answer to this question can be achieved by combining information about typical total galactic populations with studies of the viability of the accreting WD models.

1.5. *Previous Work*

Previous studies of SSSs in external galaxies have used a variety of selection criteria. In NGC 4697, e.g., Sarazin, Irwin, & Bregman (2001) identified 3 SSSs by requiring that $H\tilde{R}1 = (\tilde{M}-\tilde{S})/(\tilde{M}+\tilde{S}) = -1$ and $H\tilde{R}2 = (\tilde{H}-\tilde{S})/(\tilde{H}+\tilde{S}) = -1$, where $\tilde{S}$, $\tilde{M}$, and $\tilde{H}$ represent the numbers of counts in the bands $0.3-1$ keV, $1-2$ keV, and $2-10$ keV, respectively.[3] In their studies of the colors of X-ray sources, Prestwich et al. (2002), used the same criteria, which are satisfied by only a handful of the sources they analyzed, drawn from both M101 and M83. Less restrictive criteria were used by Swartz et al. (2002) to identify SSSs in M81. The criteria $H\tilde{R}1 < -0.5$, $H\tilde{R}2 < -0.5$ selected 12 M81 X-ray sources, 2 of which were eliminated because they are identified with foreground stars, while one is identified with a supernova remnant (SNR). Pence et al. (2002a) identified 10 SSSs in M101, but did not specify the selection criteria. The possible physical interpretation of the sources seemed to play a role, as one of the galaxy's softest sources was not counted among the SSSs, perhaps because it appears to be too luminous to be a nuclear-burning WD (Pence et al. 2002b). Kong et al. (2002a) took another approach, requiring ($H\tilde{R}2+\sigma_{H\tilde{R}2} \le -1$ *and* ([$H\tilde{R}1 < 0$,] *or* [($H\tilde{R}1+\sigma_{H\tilde{R}1} \le -0.8$]). Fourteen sources in the central $17' \times 17'$ of M31 satisfied these conditions, of which 2 were apparently identified with SNRs (Kong et al. 2002b) and 3 with possible foreground stars.

These latter criteria were developed in parallel with a study of the entire SSS population of M31 as viewed by *Chandra* (Di Stefano et al. 2002b, 2003). It was clear, however, that not all of the sources identified by these criteria were equally good candidates for the class. We therefore began by developing strict selection conditions (Di Stefano & Kong 2003 a). These criteria, the so-called HR (hardness ratio) criteria, are the first set of conditions applied in the algorithm presented here. The full algorithm we present here allows us to identify SSSs

[3] We use tildes in these expressions because our own definitions of the soft, medium, and hard X-ray bands is slightly different (see §3).

that are, e.g., at the high-T end (usually taken to be ~ 100 eV) of the class, even if they are highly absorbed. It also covers cases in which a small fraction of the emitted radiation is reprocessed and reemitted in the form of photons of higher energy. In addition the full algorithm allows us to identify sources that may be somewhat hotter than "classical" SSSs. This is the first paper to present the full algorithm, and the companion paper tests its efficacy by studying the results of applying it to data from 4 galaxies (Di Stefano & Kong 2003 b). It has also been applied to *Chandra* data from M31 (Di Stefano et al. 2003 a), and from M104 (Di Stefano et al. 2003 b).

In §2 we give an overview of physical models for VSSs, the class of source that motivated this work. In §3 we provide a phenomenological definition of SSSs designed to help select sources with the physical characteristics discussed in §2. In §4 we outline and test a sequential set of selection criteria that can be applied algorithmically to select SSSs as well as sources that are slightly harder (QSSs), in external galaxies. §5 is devoted to summarizing our conclusions.

2. PHYSICAL MODELS FOR LUMINOUS SUPERSOFT X-RAY SOURCES

For most classes of astronomical objects, the distinctive phenomenological characteristics used to identify their members are clearly related to the distinctive physical characteristics that define their fundamental nature. In the case of SSSs, however, the connection between the phenomenological definition and the gross physical properties is not unique. The broad range of temperatures and luminosities that characterize SSSs can be associated with many different types of physical systems. Analogous statements apply to the new class of QSSs. In this section we provide an overview of physical models for VSSs.

2.1. *WD Models for Supersoft X-Ray Sources*

SSS-like emission is expected from hot WDs. Approximately half of the SSSs with optical IDs in the Milky Way and Magellanic Clouds are systems containing hot white dwarfs: symbiotics, recent novae, the central stars of planetary nebulae. In most of these systems, the high temperatures and luminosities are associated with episodic nuclear burning, or with cooling subsequent to nuclear burning. The question that was raised by the discovery of binary SSSs like CAL 83 and CAL 87 is whether the soft luminous emission from them and from some of the other mysterious SSSs is due to quasi-steady nuclear burning of matter accreted by a WD from a Roche-lobe-filling companion.

Conceptually, there is a natural place in the pantheon of accreting WDs, for WDs in contact systems with high-enough accretion rates to permit quasi-steady nuclear burning. Among the accreting WD systems that dominated studies before the discovery of SSSs were cataclysmic variables (CVs) and symbiotics. In CVs the accretion rates are low (typically $\leq 10^{-9} M_\odot$ yr^{-1}) and the observed luminosities can be explained by accretion power. The accretion rates are low because, although the donor fills its Roche lobe, the mass ratio (M_{donor}/M_{WD}) is typically small and the donor is typically not evolved. In systems with larger mass ratios, the accretion rate should be larger, in some cases large enough ($\sim 10^{-7} M_\odot$ yr^{-1}) that the accreting material would be burned in a quasi-steady manner. Although the appearance of such systems would be quite different from that of normal CVs, especially because the luminosity would be $10-100$ times larger than the accretion luminosity, which would itself be larger than typical, they could represent an epoch of normal CV lifetimes, as follows.

(1) When Roche lobe overflow of a main-sequence star more massive than the WD begins, there could be a brief ramp-up time ($\sim 10^5$ yrs), during which the mass-transfer rate would be below the value needed for nuclear burning. The system might appear to be a CV, although with a brighter donor star than is typical of CVs.

(2) The accretion rate reaches the value needed for quasi-steady nuclear burning, driven by the thermal-time-scale adjustment of the donor to a shrinking Roche lobe. There ensues an epoch during which high luminosities would be generated by nuclear burning, with kT in the SSS range; the system would be a close-binary SSS (CBSS). The CBSS era ends after $\sim 10^7$ years, roughly the thermal time scale of the donor, when the mass ratio has reversed. After the system cools, the SSS behavior ends.

(3) The donor, which is now less massive and which is no longer stressed by a quickly shrinking Roche lobe, may underfill its Roche lobe for some time. Eventually, either due to dissipative processes or to its own evolution and expansion, the donor will again fill its Roche lobe and the system may again appear to be a CV.

(4) If dissipative processes were responsible for initiating the second epoch of mass transfer, then the system would simply be a normal CV, following a standard evolutionary track.

We also note that

(5) If stellar evolution played the key role in re-establishing contact, then the orbital period will increase as mass transfer proceeds. in some systems, the donor's envelope would be exhausted before the donor became very evolved. In others, the donor would become a full-blown giant. In the latter case, some systems could again experience an epoch of high-mass transfer and SSS-like behavior. These systems would be wide-binary SSSs (WBSSs).

(6) Wide binary SSSs are more commonly expected when the donor first fills its Roche lobe as a giant. Some WBSSs would be virtually indistinguishable from symbiotic systems.

The donor stars in most symbiotics are thought to feed the WD through winds, rather than through Roche-lobe overflow. Because the donors are very evolved, the rate of wind capture by the WD can be high enough that episodic or quasi-steady nuclear burning can occur. There is good evidence that the high luminosities of symbiotics are powered by nuclear burning, which may be episodic in some systems or steady in others.

Thus, quasi-steady-nuclear burning WDs in which a companion fills its Roche lobe is a natural extension of the class of CVs, with CVs representing the lower-accretion-rate systems. More massive and/or more evolved donors lead to supersoft binaries. The Roche-lobe filling SSS binaries (SSBs) with the most evolved donors have much in common with symbiotic binaries. SSBs therefore form a natural bridge between CVs and symbiotics, as they comprise a natural extension of both classes, producing a unified picture of accreting WDs.

2.1.1. *The Close-Binary SSS Model*

The close-binary SSS (CBSS) model was designed to explain the phenomenon of binary SSSs which, like the flagship sources CAL 83 and CAL 87, have orbital periods in the range of tens of hours, and estimated bolometric luminosities $\sim 10^{37}-10^{38}$ ergs

s^{-1}.[4] (See van den Heuvel et al. 1992; Rappaport, Di Stefano, & Smith 1994 [RDS].) The range of observed orbital periods implies a range of Roche lobe radii compatible with the size and mass of donors that could in fact meet these requirements. The model is therefore roughly consistent with the data on the known systems. At present, most of the known SSSs with optical IDs that do not place them in an already-understood-class of hot WD system are considered to be candidates for the CBSS model.

First principles estimates based on a population synthesis study to determine how many such CBSSs should be active in a galaxy such as our own found that there are likely to be on the order of 1000 presently active CBSSs in the Milky Way with $L > 10^{37}$ ergs s^{-1} (RDS; Yungelson *et al.* 1996). Studies of the effect of absorption then confirmed that all but a fraction of a percent of these systems would not have been detected by ROSAT (Di Stefano & Rappaport 1994).

In spite of the fact that the CBSS model is self-consistent, it has remarkably little direct observational support. There are, however, indirect signs that some CBSS candidates may be well-described by the model. These signs include the following.
(1) There are well-defined regions in the H-R diagram where steady nuclear burning has been predicted to occur. Determinations of SSS temperatures and luminosities thus far have been subject to significant uncertainties. Nevertheless, some (but not all) CBSS candidates seem to occupy regions of the H-R diagram consistent with quasi-steady nuclear burning. At present, until Chandra's low-energy calibration is better understood and/or more XMM data become available, the uncertainties are too large to allow apparent placement in the H-R diagram to confirm or falsify the conjecture that any particular CBSS candidate contains a nuclear-burning WD.
(2) The X-ray spectra (most of which are still fairly crude) are reasonably well-fit by WD atmosphere models (van Teeseling et al. 1996). Both *Chandra* and *XMM* grating spectra of selected SSSs are beginning to be analyzed, and will allow us to test the applicability of WD atmosphere models in detail. There is published work on just one system, CAL 83 (Paerels et al. 2001). There are clear disagreements between the WD atmosphere models applied to the data so far and the observed grating spectra. It remains to be seen if these can be resolved.
(3) Nuclear-burning WDs should have accretion disks with distinctive features (Popham & Di Stefano 1996). This is because the amount of energy provided by the WD in the form of heat and radiation, is ~ 10 times greater than the accretion energy. The inner regions of such a disk are thick and very hot, contributing to the total soft X-ray emission. The disk geometry flares at large radii. It cools with distance from the central WD, and is the dominant source of radiation at ultraviolet and optical wavelengths. The optical and UV observations of several CBSS candidates are consistent with the first-principles disk predictions, and this may be the strongest indication that CBSSs contain accreting objects surrounded by reprocessing-dominated disks (Popham & Di Stefano 1996). In addition, the first-principles predictions of disk geometry are in general agreement with a model of CAL 87 that was constructed to explain the eclipse profile of that system (Meyer-Hofmeister, Schandl, & Meyer 1997).
(4) Some CBSS candidates have been observed to have jets with velocities roughly compatible with the escape velocity from a WD. Since, however, objects more compact than WDs can be surrounded by WD-sized photospheres, it may be possible for such winds to originate well below the photosphere, and to escape from a region around the poles. If so, the resulting velocities could be comparable to those observed.

2.2. *Other Nuclear Burning WD Models*

2.2.1. *Symbiotics*

In symbiotic systems, the donor star is very evolved. In most cases it is thought that the donor does not fill its Roche lobe but that the WD accretes mass by capturing a small fraction of the donor's wind. Since the donor may be losing mass at $10^{-6} - 10^{-4} M_\odot$ yr^{-1}, the WD accretion rate can be high enough to allow either episodic or quasi-steady nuclear burning. Symbiotics form a well-studied class and there is evidence from several directions that the model described above is correct. The existence of symbiotics is, therefore, one of the strongest arguments that nuclear burning may fuel high luminosities and temperatures comparable to those measured in SSS binaries.

2.2.2. *Nova-Like Variables and Bright CVs*

The effects of absorption make it difficult to discover SSSs in the disk of the Milky Way; even bright, hot SSSs in the Galactic disk can be found in surveys like *ROSAT's All-Sky Survey* only if they are within about 1 kpc of Earth (Di Stefano & Rappaport 1994). Fortunately, two methods that do not depend on X-ray surveys have been able to identify previously unknown Galactic SSSs with temperatures and luminosities lower than those of any discovered via surveys.
Vy Scl stars: The pattern of optical time variability of the SSS RX J0513.9-6951 (Alcock et al. 1996, Southwell et al. 1996), was observed by Brian Warner (private communication) to be similar to that of members of the Vy Scl subclass of nova-like variables. Because the soft X-ray emission from RX J0513.9-6951 turned on during its optical low-state, we monitored Vy Scl stars and obtained ToO time to observe one such system, V751 Cyg, during its optical low state. During this occasion, it was observed to have a bolometric luminosity of 6.5×10^{36} ergs $s^{-1}\,(D/500pc)$, where D is the distance to the system, and $kT = 15^{+15}_{-10}$ eV (Greiner et al. 1999, Greiner & Di Stefano) This luminosity is several orders of magnitude larger than expected due to accretion alone, making a strong case for nuclear burning.
Bright CVs: If a CV appears so bright that its luminosity cannot be explained by accretion alone, then it may be a candidate NBWD (Patterson et al. 1998, Steiner & Diaz 1998). V Sge has been observed to exhibit a soft state (Greiner & van Teeseling 1998), but, for realistic values of absorption, the estimated luminosity is far too low ($\sim 10^{32} - 10^{33}$ erg s^{-1}) to describe a canonical SSS. Although by invoking additional absorption, it is possible to find a physical solution with $kT \sim 17$ eV and $L \sim 10^{36}$ erg s^{-1}, the SSS nature remains unconfirmed.

Nova-like variables and other CVs are thought to contain accreting WDs. The discovery of soft X-radiation from V751 Cyg, emitted at luminosities far in excess of what what could be provided by accretion, therefore constitutes indirect evidence that episodic or quasi-steady nuclear burning may be responsible for the high luminosity in some SSBs. Available evidence

[4] The range $\sim 10^{37} - 10^{38}$ ergs s^{-1} was suggested by early analyses of the ROSAT data that used blackbody fits. Some of these estimates were later revised when WD model atmosphere models were applied.

for V Sge is somewhat weaker, but may also be interpreted as supporting the SSB model (van Teeseling & Greiner 1998). There are a number of other CVs for which there is evidence of energy emission from a CV in excess of the energy available from accretion. Because nuclear burning near the surfaces of lower-mass WDs should yield smaller luminosities and lower temperatures, the WD mass in SSSs in this category are likely to be smaller. Note that V751 Cyg, and possible some of the other VY Scl stars, possibly V Sge and other high-L CVs, appear to represent the low-L/low-T extension of SSBs, and the high-L/high-T extension of CVs.
An interesting point is that, if a significant fraction of nova-like variables or anomalously bright CVs exhibit SSS states, the total number of SSBs in the Galaxy could be very large. For example, in a 1 kpc region surrounding the sun, these systems outnumber other CBSS candidates by a factor of more than 10. These systems could have been (indeed may already have been) detected in M31 (Di Stefano et al. 2002a, 2003), but would not have been detectable in the exposures taken of the 4 galaxies we consider in the companion paper (Di Stefano & Kong 2003 b).

2.2.3. *Wide-Binary SSSs (WBSSs)*

The high accretion rates needed for episodic or quasi-steady nuclear burning can also be achieved in contact binaries with orbital periods larger than those of CBSSs. In these cases, the nuclear evolution of a Roche-lobe filling giant can drive the required high mass transfer rate (Hachisu, Kato, & Nomoto 1996; Di Stefano & Nelson 1996). While optical emission from CBSS binaries comes predominantly from the irradiated disk (Popham & Di Stefano 1996), SSSs with giant donors may be optically characterized by emission from the donor, and such systems could therefore have detectable optical counterparts even in external galaxies.

2.2.4. *Irradiation-Driven Winds*

Two SSBs, 1E0035.4-7230 and RX J0537.7-7034, have short orbital periods ($3-4$ hours) and mass functions that consistent with a donor star of mass smaller than that of the WD. In such systems, mass transfer could not be mediated by the same processes as those assumed for a CBSS. Instead, an irradiation-driven wind has been postulated as the source of mass donated to the WD (see, e.g., van Teeseling & King 1998). Irradiation-driven winds are likely to play a role in most SSBs; in the binaries described above, they are the drivers of mass transfer.

2.3. *Alternatives to WDs*

2.3.1. *Neutron Stars*

Kylafis & Xilouris (1993) found that near-Eddington accretion onto neutron stars could be associated with large photospheres, consistent with the effective temperatures of SSSs. The extent of the radial flow can determine whether each neutron star with accretion rate within $\sim 10\%$ of the Eddington limit appears as an SSS (for an extended radial flow) or as a standard X-ray binary dominated by harder emission. Although it was not clear that the extended radial flow and large photosphere were to be expected, neutron star models received observational support with the discovery of an unusual transient X-ray pulsar, RX J0059.2-7138 (Hughes 1994). RX J0059.2-7138 has been observed to have a soft (~ 30 eV) unpulsed component that is highly luminous ($\sim 6.7\times10^{38}$ ergs s^{-1}; $N_H \sim 8.8\times10^{20}$ cm^{-2}. (See also Kohno, Yokogawa, & Koyama 2000.) In fact, if we were not in the pulsar's beam, RX J0059.2-7138 would simply be classified as an SSS. It is unlikely that RX J0059.2-7138 is an anomaly. In fact, Her X-1, a galactic X-ray X-ray pulsar, has long been known to have a luminous time-variable soft component (Shulman et al. 1975, Fritz et al. 1976).

2.3.2. *Black Holes*

An accretion disk around an intermediate-mass BH is expected to yield SSS emission. Consider an accreting Schwarzschild BH of mass M. If the accretion disk is optically thick but geometrically thin, and if the disk extends down to the last stable orbit, the temperature of its inner rim is roughly

$$k\,T = 42\,eV \left(\frac{1000\,M_\odot}{M}\right)^{\frac{1}{2}} \left[\left(\frac{0.1}{\alpha}\right)\left(\frac{L_{obs}}{3\times10^{37} ergs^{-1}}\right)\right]^{\frac{1}{4}}, \quad (1)$$

where M is the mass of the BH, α is the efficiency factor, and L_{obs} is the observed luminosity. This equation illustrates that, for a broad range of values of the BH mass and of the luminosity, SSS emission is expected.

It is less certain whether stellar-mass BHs can emit spectra dominated by a soft component, but if extended photospheres are possible for accreting NSs, they may also be possible for accreting stellar-mass BHs. A BH nature has been suggested for CAL 87, e.g., (Cowley, Schmidtke, Crampton, & Hutchings 1990, 1998; Hutchings, Crampton, Cowley, & Schmidtke 1998) Orbital observations of CAL 87 have suggested that the primary may be a star with mass between $1.3 M_\odot$ and $4 M_\odot$. The mass estimate hinges on the assumed location from which line emission emanates. The highest estimated mass might correspond to a black hole (BH) accretor.

2.3.3. *Stripped Cores of Tidally Disrupted Stars*

At the center of most, if not all, galaxies is thought to be a massive ($\sim 10^6-10^9 M_\odot$) BH. A star of mass M_* and radius R_* can be disrupted by approaching within R_t of the BH.

$$R_t = \left(\eta^2 \frac{M_{bh}}{M_*}\right)^{\frac{1}{3}} R_*, \quad (2)$$

M_{bh} is the mass of the BH, and η is a parameter of order of unity. The disruption leaves an end-product, the giant's hot dense core. The core remains hot ($T > 10^5$ K) and bright ($L > 10^2 L_\odot$) for 10^3-10^6 years, thereby providing the longest-lasting signal of a tidal disruption (TD). This scenario was proposed by Di Stefano, Greiner, Garcia, & Murray 2001. Given the expected rate of TDs, in a galaxy such as M31, several of these remnants could be active at any given time. Some stripped cores are expected to be WDs or pre-WDs, and some are expected to be helium stars.

The possibility that SSSs in the center of nearby galaxies could be signatures of TDs is interesting, particularly because other signatures of TDs are so difficult to identify with confidence. The complementary signature most considered is an event due to the accretion of a portion of the disrupted star's envelope by the BH (Hills 1975, Lidskii & Ozernoi 1979, Gurzadyan & Ozernoi 1980, Rees 1988). The associated accretion event can last for months or decades, with luminosities possibly as high as $\sim 10^{44}-10^{46}$ erg/s. There is a growing body of data on UV and X-ray flares that may be consistent with these sorts of accretion events (see references in Di Stefano et

al. 2001). It is nevertheless difficult to establish a definite link between observed flare events and accretion events, so information about stripped cores in nearby galaxies would be important.

The possibility of studying the stripped cores of disrupted stars is an important motivation of the search for SSSs in the central regions of galaxies.

2.4. *Models for Contaminants*

In this section we have so far focused on models in which the SSSs we discover are luminous X-ray binaries. We expect, however, that other types of objects will produce the same broadband X-ray signatures. SNRs form the primary class of SSS "contaminants" that are luminous ($L_X > 10^{36}$ erg s^{-1}), and which are actually members of the galaxy being observed. In M31, 2 SSSs are SNRs. Interestingly, one of these M31 SNRs is among the softest sources in M31. Most of the other 33 M31 SSSs we identified using the criteria presented in this paper, are highly variable; many are transients. We therefore know that SNR contanimants form only a minor portion of the SSSs in M31. In Di Stefano & Kong (2003 a), we studied the available data on the variability of SSSs in 4 more distant galaxies (M101, M83, M51, and NGC 4697; see also Di Stefano & Kong 2003 b). Although the limited time coverage of the observations we studied allowed only the brightest sources to be checked for variability, we did find evidence of variability on time scales of a year. This is consistent with an X-ray binary nature for the majority of bright SSSs.

Knots in diffuse emission from the galaxy can also have very soft spectra, and they may be misidentified as SSSs when they cannot be spatially resolved. This is most likely to occur near the centers of galaxies with a significant diffuse soft component, but can happen in any location in which the X-ray emission appears to be dominated by diffuse emission. If the sources are bright or the time sampling is good, time variability can help to identify which sources in regions of diffuse emission may be X-ray binaries; observations at other wavelengths may be helpful in finding counterparts to extended objects. In the absence of such complementary information, however, SSSs discovered in regions of diffuse emission should not be assumed to be X-ray binaries.

Other systems identified by our algorithm are dim foreground objects or bright background objects. Foreground stars can emit soft X-rays. In many cases such stars will have been identified by optical surveys and can be ruled out as luminous X-ray binaries. In high surface brightness regions of the observed galaxy, however, the survey of foreground stars may be less complete, and we may not be able to identify which SSSs are foreground stars. A further complication is that the soft X-ray emission from foreground stars can be highly variable, so variability cannot be taken as a signature that the SSS is an X-ray binary. Distant soft AGN can also be selected as SSSs; observations at other wavelengths can help to identify some, but probably not all of these. Further, some nearby magnetic CVs can also be selected as SSSs; it may be difficult to identify such sources at other wavelengths.

The standard method to estimate the contribution of foreground and background sources is to use results derived from deep field surveys (Giacconi et al. 2001, Brandt et al. 2001). Because, however, we are specifically interested in SSSs, which have not yet been studied in the deep fields, we have used another approach, sketched below, and discussed in more detail in (Di Stefano et al. 2003). Briefly, we have applied our algorithm to *Chandra* data from several fields analyzed by the ChAMP team. We consider only fields located away from the Galactic plane, and containing no clusters or galaxies. In such fields, we generally we find $1-3$ VSSs in the S3 CCD. When, therefore, in observations of an external galaxy, we discover tens of VSSs in the S3 CCD, we can assume that the majority of them are associated with the galaxy.

Finally, we note that, although SNRs, foreground stars, and other "contaminants" do not dominate the VSSs we identify with galaxies, our algorithm does provide an efficient way to search for X-ray active SNRs and for a subset of foreground stars.

3. PHENOMENOLOGICAL DEFINITION OF LUMINOUS SUPERSOFT X-RAY SOURCES

Our phenomenological definition should select sources described by the physical models discussed above. The WD models alone define a broad range of temperatures, from $kT < 10$ eV up to ~ 150 eV.[5] For example, while V751 Cyg had a best fit temperature with $kT < 10$ eV, a $1.4 M_\odot$ WD with Eddington-luminosity nuclear burning on its surface would have $kT \sim 150$ eV. NBWD luminosities range from $\sim 10^{35}$ erg s^{-1} up to the Eddington limit for a $1.4 M_\odot$ object ($\sim 2\times 10^{38}$ erg s^{-1}). The stripped core of a high-mass star might have a temperature near the low end of the temperature range, but a luminosity in excess of 10^{39} erg s^{-1}. Accreting BHs could have even higher luminosities, with temperatures in the SSS range or even higher.

3.1. *Unique Features of SSSs*

The sensitivities of the detectors used for X-ray astronomy tend to peak for photons with energies near or above 1 keV. Until the advent of *Einstein* and then *ROSAT*, it was difficult to study sources with energy distributions peaked significantly below 1 keV. It was also difficult to detect and study such sources by using detectors effective at UV or EUV wavelengths, since this radiation is readily absorbed by the ISM. When, therefore, the *ROSAT All Sky Survey* discovered several dozen sources with little or no emission above 1 keV, it was an important result.

Figure 1 illustrates the key features of SSS spectra, versus the spectra of other X-ray sources. We consider a sequence of thermal models, with temperatures ranging from kT = 20 eV to kT = 2 keV within each large panel, and N_H ranging from 4.0×10^{20} cm^{-2} to 2.5×10^{22} cm^{-2} from the top left panel to the bottom right panel. Spectra of sources with $kT < 100$ eV are shown in red, as these would generally be considered to be SSSs; green marks sources with 100 eV $< kT <$ 1 keV, while blue shows the spectra for the hottest sources we considered. Each model was used to simulate a source located in M31 (at a distance of 780 kpc). We used PIMMS to compute the expected count rate. The variable along the vertical axis is the log of the number of counts detected by ACIS-S in 10 ksec. Values along the horizontal axis correspond to bin numbers: 1 = 0.3−0.5 keV, 2 = 0.5−0.7 keV, 3 = 0.7−0.9 keV, 4 = 0.9−1.1 keV, 5 = 1.1−1.5 keV, 6 = 1.5−2.0 keV, 7 = 2.0−7.0 keV.

For small values of N_H, represented here by $N_H = 4.0\times 10^{20}$ cm^{-2}, the spectra of SSSs peaks in bin 1 (photon energies < 0.5

[5] The value 150 eV is an absolute maximum for nuclear-burning WD models. It corresponds to the Eddington luminosity emitted from an effective radius equal to that of a Chandrasekhar mass WD. In fact, the photospheric radius is expected to be larger; only if some of the radiation is scattered to higher energies, or if X-rays are emitted by a small portion of the photosphere, would such a high effective temperature be possible.

keV) and declines to 0 by bin 6 (photon energies between 1.5 and 2.0 keV). The decline is steepest for SSSs of the lowest temperatures; 25 eV sources cut off above 0.5 keV, 40 eV sources cut off above 0.7 keV, 55 eV sources cut off above 0.9 keV, and so on. For 100 eV sources, there are a small number of counts above between 1.5 and 2.0 keV. The comparison with sources of higher temperature ($kT > 250$ eV) is striking: the detectable spectrum of high-temperature sources is either peaking or still rising in bins where the SSSs are cut off. As N_H rises, photons are lost in all bins, but the erosion is sharpest at lowest energies. The total count rate for SSSs declines sharply with increasing N_H, with contributions from the lowest bins falling to 0 first.

The spectral characteristics of a 100 eV sources are significantly different from those of a 250 eV source. If we are to use a phenomenological definition of SSSs, it is important to identify a temperature between these two temperatures that marks the transition between SSSs with thermal spectra and other thermal sources. Figure 3 shows results parallel to those of Figure 2, but for kT between 125 eV and 225 eV. At 175 eV, there is some hard emission in bin 7 for all values of N_H. We have therefore chosen 175 eV to define the boundary temperature for SSSs: sources with $kT < 175$ eV are SSS. It is likely that a thermal spectrum does not provide a good fit to all SSSs. We therefore also consider power-law models. Because sources with $\alpha \geq 3.5$ are rare, we choose this as our definition of power-law-fit SSSs.

3.2. *A Phenomenological Definition of SSSs*

If any source has enough counts that a spectrum can be well fit, then the source is an SSS if any of the following conditions are met.
(1) The spectrum is well-fit by a blackbody model with $kT < 175$ eV,
(2) The spectrum is well-fit by a power-law model with $\alpha \geq 3.5$,
(3) Whatever the best fit model, less than 10% of the energy is carried by photons with energy greater than 1.5 keV.

The reason for adding condition (3) is that, even if the emitter in an SSS can be well-described by either a thermal or power-law model, interactions with matter in the vicinity of the emitter can upscatter some of the photons. The choice of 10% is rather arbitrary; future studies of larger numbers of SSSs may suggest that this criterion be altered. For now we allow as much as 10% of the energy to come in at energies above 1.5 keV, because this is roughly consistent with efficient reprocessing or with, e.g., the presence of a companion emitting a strong shocked wind. We do not allow higher values, simply because we want to reserve the SSS classification for sources whose spectrum is clearly dominated by the soft component.

Most sources in external galaxies provide too few photons for a meaningful spectral fit. In these cases, we must try to select sources that would satisfy the above criteria, had we been able to collect enough photons. The selection criteria are described in section 4 and in the flowchart of Figure 3. We propose that any source that passes the test defined by these procedures be provisionally identified as a very soft X-ray source.

4. THE SELECTION OF SUPERSOFT SOURCES

4.1. *Overview of the Selection Criteria*

In this section we outline our selection criteria. Because we define 9 sub-categories, the results may seem complicated. We therefore begin by pointing out that the categories have a simple overall structure. Details are provided in the Appendix.

4.1.1. *"Classical" Supersoft Sources*

There are 2 separate set of criteria that select sources most likely to be as soft as the standard SSSs first discovered in the Magellanic Clouds. These 2 sets of conditions are the HR conditions and the 3σ conditions. In a separate paper we have written about the HR conditions and their results when applied to 4 galaxies: M101, M83, M51, and NGC4472. The 3σ conditions mirror the HR conditions, but should be able to identify SSSs with slightly lower count rates. Any source satisfying either the HR and 3σ conditions will be referred to as a "classical" SSS or simply as an SSS.

4.1.2. *Quasisoft Sources*

Many X-ray sources which are very soft may not satisfy either the HR or 3σ conditions. Consider, e.g. a 125eV source located in M31. If it is luminous enough, we will detect a significant number of photons in the M band. If, in addition, the source is located behind a large gas column, we may receive few photons in the S-band. In addition, because *ROSAT* did not have good high-energy sensitivity (> 2 keV) and because we do not know enough about physical models for SSSs to eliminate the possibility that some have a relatively hard tail, it is important to retain and classify very soft sources that do not satisfy either the HR or 3σ conditions. We therefore introduce 2 categories of weaker conditions. Any source satisfying one of the weaker conditions is referred to as a quasisoft source (QSS). Each QSS sub-category is defined by specific conditions described in the appendix. A brief explanation of each category is given here.

There are two types of QSS selection criteria. The first requires that there be little or no hard emission ($H/\Delta H < 0.5$) Any source fulfilling this condition falls into one of the so-called "noh" categories. Depending on how dominant the S and M bands are, QSSs with little or no hard emission sources are labeled NOH (for no hard emission), MNOH (no hard emission but a 3σ detection in M, even though the broadband spectrum is dominated by soft photons), SNOH (no hard emission, little M emission, but a 3σ detection in S), and FNOH (the spectrum is flatter than in the other noh categories.)

The second type of QSS selection criteria identifies sources which may emit some hard radiation ($H/\Delta H > 0.5$), but in which the soft component clearly dominates. These sources are labeled HR_1, $3\sigma_1$, or σ.

4.2. *Distinctions between SSS and QSS*

It is important to note that, in many cases, the only distinction between SSSs and QSSs may be operational - i.e. in the way members of each category are selected. There are some cases in which identical sources observed under different condition, may be put in different (QSS vs SSS) categories. As *Chandra's* low-energy sensitivity declines, e.g., many sources that would have qualified as SSSs if observed in AO1 will be selected as QSSs, even if their luminosity and spectral characteristics are constant. Other QSSs may have spectra that are genuinely harder than SSSs - they may, e.g., have higher temperatures. ($kT \sim 200$ eV) or they may be dominated by very soft radiation, but may included a power-law tail.

It is a separate question, however, whether QSSs and SSSs have different physical natures. Any SSSs which are nuclear burning WDs should not have $kT \gtrsim 150-175$ eV. Hotter

sources are therefore unlikely to be nuclear-burning WDs. Accreting NSs or accreting intermediate-mass BHs could, however, have spectra that put them in either the SSS or QSS category.

4.3. *Tests*

There are two questions we must address. First, do the conditions described above select a large fraction of genuine SSSs? Second, what fraction of and what kinds of non-SSS sources are mis-identified as SSSs?

To answer these questions, we have tested the selection criteria on a set of thermal models. We consider sources with intrinsic luminosities between 6×10^{35} ergs s^{-1} and 1×10^{38} ergs s^{-1}, computing their fluxes as if they were in M31 (i.e., $\sim$ 780 kpc from us), computing the number of counts in each of the 7 bins described in §3.1, plus one bin $0.2-0.3$ keV. We considered a 35 ks observation, and added two σ uncertainties. We considered 10 luminosities, and for each luminosity, we considered 10 realizations, randomizing the number of counts in each bin $(0-7)$ between -2σ and 2σ of the PIMMS-computed value. We used the PIMMS software to compute the counts that would be detected, using 4 values of N_H for each source: 4.0×10^{20} cm^{-2} (red points), 1.6×10^{21} (yellow; open circles) cm^{-2}, 6.4×10^{21} cm^{-2} (green; larger open circles), 2.5×10^{22} cm^{-2}(blue; largest open circles). The lowest value is somewhat smaller than typical Galactic values of N_H along directions to M31. The largest value would correspond to directions for which the absorption within M31 was exceptionally high.

The numerical results are summarized in Tables 1, and in Figure 4. Figure 4 clearly shows that the conditions HR, 3σ, NOH, MNOH, and SNOH produce few misidentifications for thermal sources. That is, almost all selected sources with more than 10 counts and without a large intervening absorbing column (6.4×10^{21} cm^{-2} or 2.5×10^{22} cm^{-2}) have $kT<175$ eV. Some of the higher temperature SSSs (kT near or above 100 eV) are missed, however, particularly when N_H is large. The additional conditions, HR$_1$, $3\sigma_1$, σ, and FNOH help to identify these high-T, high-N_H SSSs. These further conditions, however, yield a higher rate of identifications of systems with kT on the order of a few hundred eV. Some of these medium-temperature QSSs, may be SNRs, but those we have been able to study in M31 appear to be variable on time scales of months to years, ruling out SNR models (Di Stefano et al. 2003b). Overall, 90% of SSSs (blackbodies with $kT<175$ eV) are correctly identified; only 70 of 2000"hard" ($kT>500$ eV) were misidentified; 75% of QSSs ($175\leq\ kT<500$ eV) were also selected.

4.4. *XMM Observations*

The above selection criteria were designed to optimize the selection of SSSs as simulated by PIMMS for *Chandra* ACIS-S observations. As presently formulated, they will have almost the same effect on data from *XMM*, which offers similar energy coverage but with larger effective area. We compared the sensitivity of *XMM*/PN with a thin filter and *Chandra* ACIS-S, we found that for SSSs, in the S, M, and H bands, *XMM* collects ~3, ~2, and ~3 times as many photons as *Chandra*, respectively. This suggests that the primary difference between *XMM*/PN and *Chandra* ACIS-S is the former's somewhat smaller relative sensitivity to photons in the M band. Thus, fraction of sources in the SSS-FNOH and SSS-MNOH categories may be smaller when *XMM* rather than *Chandra* data is used. Because of its larger effective area, *XMM* may do better in searching for SSSs in regions where source confusion and diffuse gas emission are not problems.

4.5. *Real Chandra Observations*

As noted in §5.2, *Chandra's* ACIS detectors have suffered degradation at low (<1 keV) energies. This degradation is time dependent and was not included in the PIMMS simulations. In the companion paper, we apply the selection algorithm to real *Chandra* ACIS-S data. Their effect will not be the same as the effect they had on the simulated data. For example, when the counts in the S bin are half of what they would have been in the simulated data, while M and H are relatively unaffected, imposing the requirement that $S>3M$, will be the same as if we had imposed $S>6M$ in the simulations. That is, the low-energy degradation makes it more difficult for an SSS to be identified. In many cases, a source that, without the degradation, might have been identified at a higher point in the hierarchy (e.g., as an SSS-HR source), will now be identified at a lower point in the hierarchy (perhaps as an SSS-MNOH or SSS-σ sources). In other cases, SSSs will simply fail to be identified as such. There is no direct cure for this latter problem, because we cannot assume that a lack of low-energy photons is due to a lack of sensitivity. Fortunately, even with the degradation, we are able to identify a significant population of SSSs in each galaxy.

5. SUMMARY AND CONCLUSION

The primary focus of the research described in this paper is to develop a systematic procedure to identify SSSs in external galaxies. To accomplish this we began by crafting an operational definition of SSSs. (See §3.2.) It is based entirely on the spectral shape: a blackbody spectral fit with $kT<175$ eV, or a power law spectral fit with $\alpha>3.5$, or any spectral fit where less than 10% of the energy is carried by photons with energy >1.5 keV. These criteria can be applied directly to sources providing enough counts to allow a good spectral fit. Since most sources in distant galaxies do not provide enough counts, we have designed a set of conditions which can be applied algorithmically to determine if the true spectrum of a low-count source is likely to satisfy the SSS criteria. Because the conditions work for high-count sources as well as low-count rate sources, we simply apply our algorithm to all sources in each galaxy to identify the SSSs. The sources are then sub-classified according to the specific conditions they satisfy.

The strongest conditions are called the HR and 3σ conditions. We have called a source an SSS if it satisfies either the HR or 3σ conditions.

We call all sources that satisfy the weaker conditions, QSSs. Some QSSs may be similar to SSSs, but perhaps more highly absorbed, or they may be genuinely harder than the canonical SSSs. The harder sources may have values of kT between roughly 175 eV and 350 eV, or may be very soft sources which include a low-luminosity hard spectral component. The QSSs with dominant spectra that are genuinely harder than those of SSSs (e.g., those with $kT>175$ eV) are almost certainly not WDs, unless the X-ray emission emanates from only a small portion of the photosphere. They may be accreting NSs or, perhaps most likely, accreting intermediate-mass BHs.

Tests with simulated data show that our criteria accomplish the following. (1) They select a majority of SSSs– 90% of thermal models. (2) They select only a small fraction of "hard" sources (4% of models with $kT>500$ eV). (3) They select a substantial fraction of quasi-soft sources. For blackbody

models, quasi-soft sources were those in the range 175 eV $< kT <$ 500 eV; 70% of these were selected.

The selection of QSSs is difficult to avoid if we are to succeed at identifying possibly absorbed high temperature SSSs (kT near 100 eV), some of which could be high-mass accreting WDs on their way to becoming Type Ia supernovae. On the other hand, the presence of QSSs in the data is intriguing, because there appear to be no known X-ray binary analogs with similar luminosities ($> 10^{36}$ erg s^{-1}) in the Galaxy or Magellanic Clouds. Some may be SNRs; repeated X-ray observations and optical emission line studies can distinguish SNRs from X-ray binaries. Those that vary in time are likely to be X-ray binaries either of a type or in a state that is not typical of nearby X-ray binaries. The discovery of such sources in real data sets thereby challenges us to understand what they are.

In the companion paper we describe how we tested the selection algorithm by applying it to real data from 4 galaxies. We verified that the spectra of the sources identified as SSSs tend to be in the range we used to define SSSs. These investigations have also yielded interesting information about extragalactic SSSs, providing some first steps toward answering the 7 questions posed in §1.3.

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APPENDIX

Selection Criteria

The selection criteria described below are also illustrated in the flow chart of Figure 3.

Three energy bins are used to define the hardness ratios: **S:** 0.1-1.1 keV, **M:** 1.1-2 keV, **H:** 2-7 keV. We employ 2 hardness ratios.

$$HR1 = \frac{M-S}{M+S} \tag{1}$$

$$HR2 = \frac{H-S}{H+S} \tag{2}$$

The selection criteria will sometimes use the numbers of counts, $C(i)$, in each of the 7 bins defined in §3.1. In addition, we consider bin $0 : 0.1-0.3$ keV. Although photons with energies in this lowest bin cannot be used to compute spectral characteristics, especially without a well-understood low-energy calibration, they can be useful to the identification of SSSs.

Hardness Ratio Conditions

The strongest set of conditions we impose are strict hardness ratio (HR) conditions. We demand that $HR1 < -0.8$ and $HR2 < -0.8$. These conditions imply that

$$S > 9M, \tag{3}$$

$$S > 9H. \tag{4}$$

We also require

$$HR1_{\triangle} < -0.8, \tag{5}$$

$$HR2_{\triangle} < -0.8, \tag{6}$$

where $HR1_{\triangle} = [(M+\Delta M)-(S+\Delta S)]/[(M+\Delta M)+(S+\Delta S)]$, and ΔS and ΔM are the one-σ uncertainties in S and M, respectively. An analogous expression defines $HR2_{\triangle}$. The conditions on $HR1_{\triangle}$ and $HR2_{\triangle}$ can be satisfied only by systems that have small relative uncertainties in the total numbers of counts. This generally implies either a high count rate or else a total absence of flux in the M and H bands, combined with low background in the S band. We denote systems that satisfy the HR conditions “SSS-HR."

When tested on thermal models as described in §4.3, the HR conditions select only systems with $kT < 175$ eV. SSS-HR sources are therefore prime SSSs.

3σ *Conditions*

To accommodate SSSs with lower count rates, we implement the following “3σ" conditions. First, we demand a two σ detection is the S band.

$$\frac{S}{\Delta S} > 2 \tag{7}$$

In addition,

$$\frac{S}{\Delta S} > 3\,\frac{M}{\Delta M} \tag{8}$$

$$\frac{S}{\Delta S} > 3\,\frac{H}{\Delta H} \tag{9}$$

When the uncertainties in S, M, and H can be approximated as $\sqrt{S}$, $\sqrt{M}$, and $\sqrt{H}$, respectively, then the 2 conditions above imply the same restrictions on the relative values of S and M and S and H as do Eqns. 3 and 4. We denote systems that satisfy the 3σ conditions “SSS-3σ."

The HR and 3σ conditions select sources based on the dominance of flux in the S band. If, however, there is a large column of gas between the source and the detector, the preferential absorption of soft photons erodes the signal in S relative to that in the other bands, so that even genuine SSSs may satisfy neither condition. Especially if the flux is small, the HR and 3σ conditions will fail to identify many SSSs. We therefore introduce weaker conditions that can identify additional SSSs, but which may also identify some harder sources. Because the SSS status of sources identified via weaker conditions is less secure, we refer to all such sources as “quasisoft" sources (QSSs). Any QSSs with high enough count rates to allow spectral fits, and for which the fits shows a low effective temperature, can then be reclassified as SSSs.

To proceed, we turn to another hallmark of SSSs: the lack of high-energy emission from many of the “classical" SSSs.

We use the condition,

$$\frac{H}{\Delta H} < 0.5. \tag{10}$$

to identify 2 branches in the identification procedure. If the condition is satisfied, we know that the source cannot be hard, and devise further tests to determine if it is soft. We refer to the path defined by these further tests as *Branch 1*. If the condition given in Eq. (10) is not satisfied, it is still possible for the source to be an SSS. *Branch 2* implements those conditions that can select SSSs while rejecting hard sources.

Branch 1: NOH

If $C(6)/\Delta C(6) \leq 1$ and $C(5)/\Delta C(5) \leq 2$, then there is at most a weak detection in the bins corresponding to medium energies. Sources satisfying these conditions are called "QSS-NOH"; they exhibit little or no emission above 1.1 keV.

If the NOH condition is not satisfied, then there is a detection above 1.1 keV. The condition $M/\Delta M > 3$, creates another bifurcation which we can follow along 2 sub-branches, *Branch 1.1* and *Branch 1.2*.

Branch 1.1: MNOH

If we have reached this point along the path, there is no hard emission, but there is significant emission in the M band. We can call the source "supersoft" only if emission in the S band dominates and if, there is a steep decline in the number of counts from the low to high energy bins. We therefore require that $\frac{S}{\Delta S} > 2\frac{M}{\Delta M}$ and $C(5) > 2.6C(6)$. Sources satisfying these conditions are designated "QSS-MNOH".

Branch 1.1: FNOH

Sources that do not satisfy the conditions for QSS-MNOH could be SSSs which are highly absorbed, or they could be sources with spectra that can best be viewed as flat in M relative to S –i.e., little emission in the soft or hard bands, e.g., a 200 eV blackbody. We call such sources "QSS-FNOH".

Branch 1.2: SNOH

If we have reached this point along the path, there is no hard emission, but there is also little flux in the M band. The source can be SSS only if there is emission in the S band. If $S/\Delta S > 3$, we use the designation "QSS-SNOH".

Branch 1.2: FNOH

If the source fails the SNOH test, it is placed in the QSS-FNOH category.

Branch 2: HR_1

In this case, $H/\Delta H > 0.5$, so there may be some hard emission. If the hard emission is nevertheless a small component of the spectrum, the source could still be an SSS. First we require that either (a) $H/T < 0.005$, where $T = S+M+H$, or (b) both $S/\Delta S > 3$ and $H/\Delta H < 1$. In addition, we require the same conditions on HR2 required for the "HR conditions": $HR2 < -0.8$ and $HR2_{\Delta} < -0.8$. At this point, however, we relax the conditions on HR1. That is, we allow for the possibility that absorption has eroded the flux in the S band relative to the flux in the M band. The new conditions on HR1 are: $HR1 < -0.5$ and $HR1_{\Delta} < 0$. These conditions could, e.g., be satisfied by an absorbed 100 eV SSS. Sources satisfying these conditions will be referred to as "QSS-HR_1".

Branch 2: "$3\sigma_1$" conditions

The $3\sigma_1$ conditions represent a somewhat relaxed version of the 3σ conditions. We require a two-σ detection in S, $S/\Delta S > 2$, and that the hard flux be a small fraction of the total flux: $H/T < 0.005$. As before, we require $S/\Delta S > 3H/\Delta H$. But we relax the condition (8), replacing it with $S/\Delta S > M/\Delta M$. Systems satisfying this set of conditions are designated "QSS-$3\sigma_1$".

Branch 2: "σ" conditions

Sources with $H/T < 0.05$, and $\frac{S}{\Delta S} > 3$ are designated "QSS-σ".

Branch 2: NOT SSS

The remaining sources are, for the purposes of this classification scheme, not SSSs.

TABLE 1
TEST OF THE SELECTION ALGORITHM

Thermal	All	kT < 175 eV	175 eV ≤ kT < 500 eV	kT ≥ 500 eV
N_{total}	6800	3200	1600	2000
Low L	918	828	49	41
HR	1329	1328	1	0
3σ	143	136	7	0
NOH	128	116	7	5
SNOH	53	50	3	0
FNOH	459	230	210	19
MNOH	97	62	35	0
HR_1	299	75	224	0
$3\sigma_1$	248	42	206	0
σ	520	16	500	4
Not SSS & QSS	2605	317	358	1930

Note. — N_{total} is the total number of sources generated. "Low L" sources yielded 4 or fewer counts; we did not consider these sources further. One thermal model with more than 4 counts exhibited flux in only the hard band ($S+M=0$;) we did not consider these sources further.

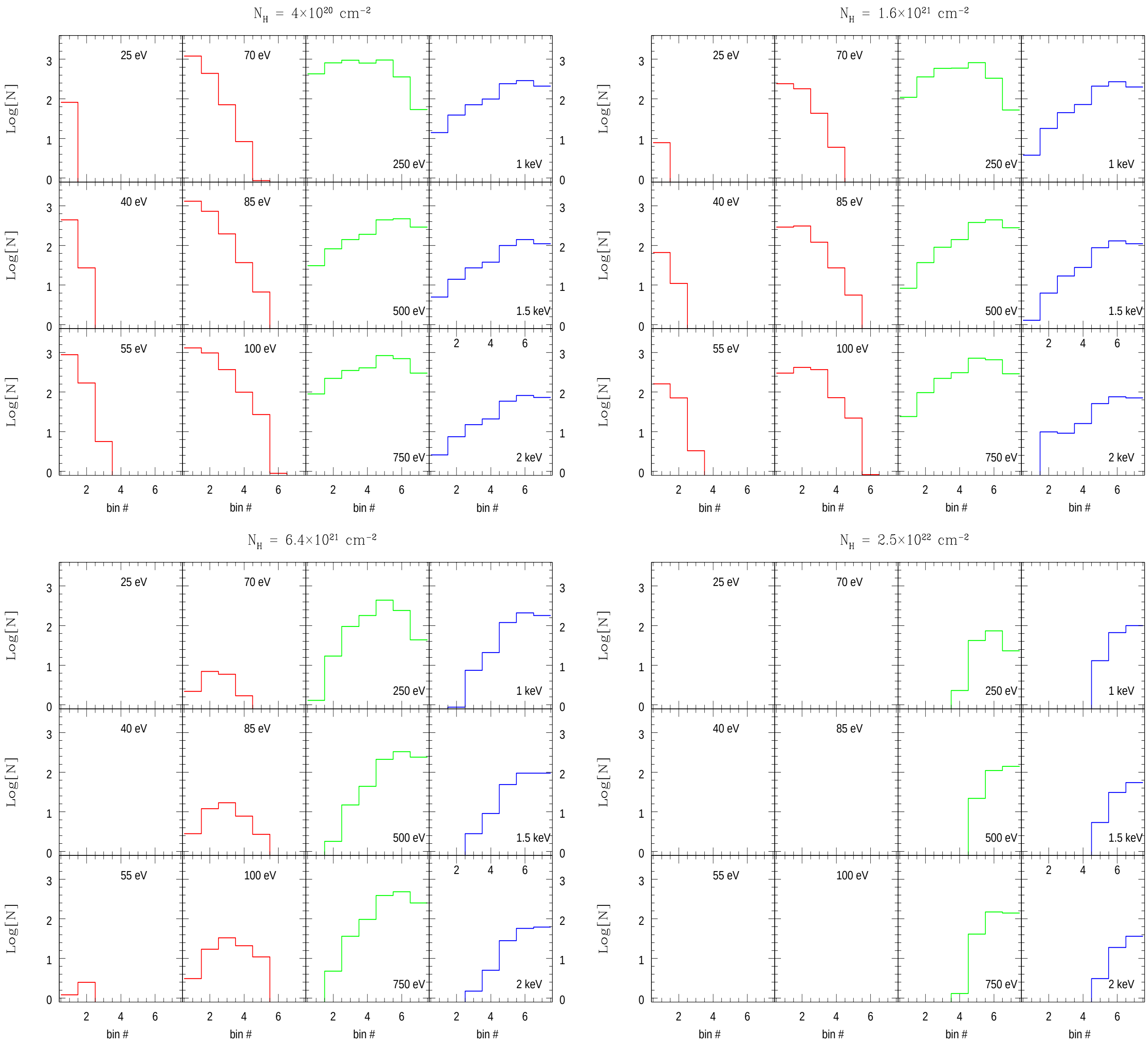

FIG. 1.— PIMMS Results: *Log*[*N*] vs energy bin number. *N* is the number of counts detected in each bin when a 10^{38} erg s^{-1} source is placed in M31 (d = 780 kpc) and is observed for 10 ksec. The energy bins are defined in §3.1.

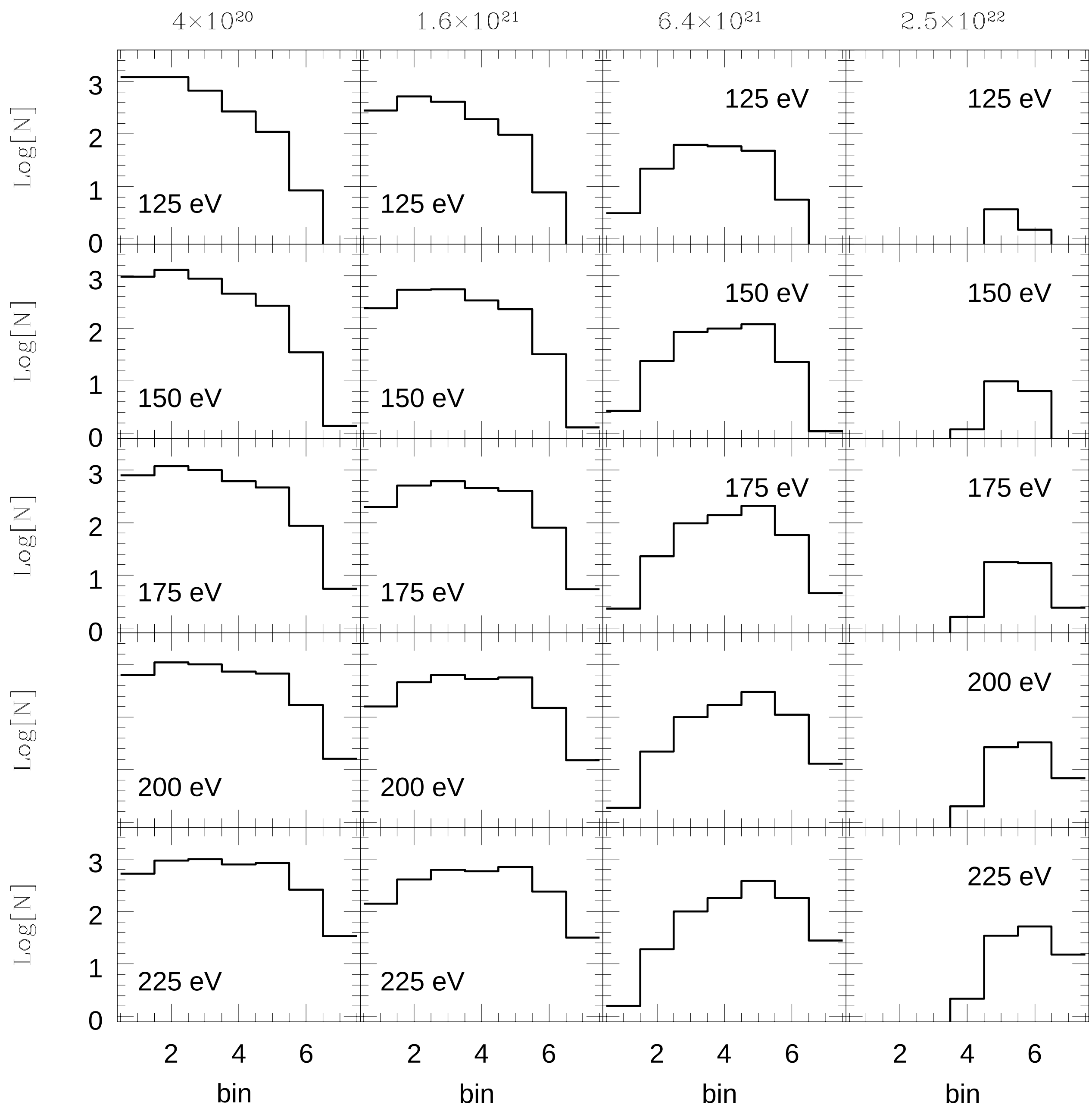

FIG. 2.— Same as Figure 1.

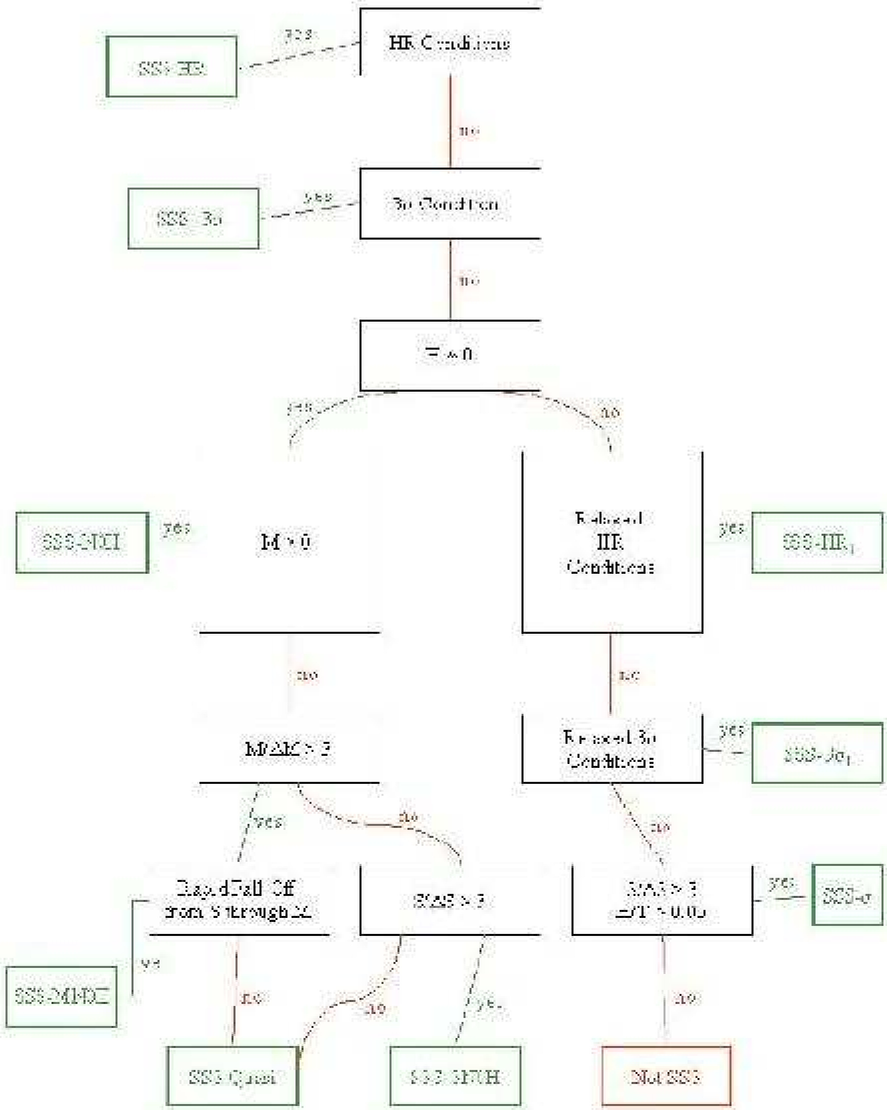

FIG. 3.— Flow chart of the selection algorithm. In principle, spectral fits of all high count rate sources can be used to identify the brightest SSSs even before the HR conditions are applied. In practice, we have found that the high count rate sources were identified by the selection process sketched here.

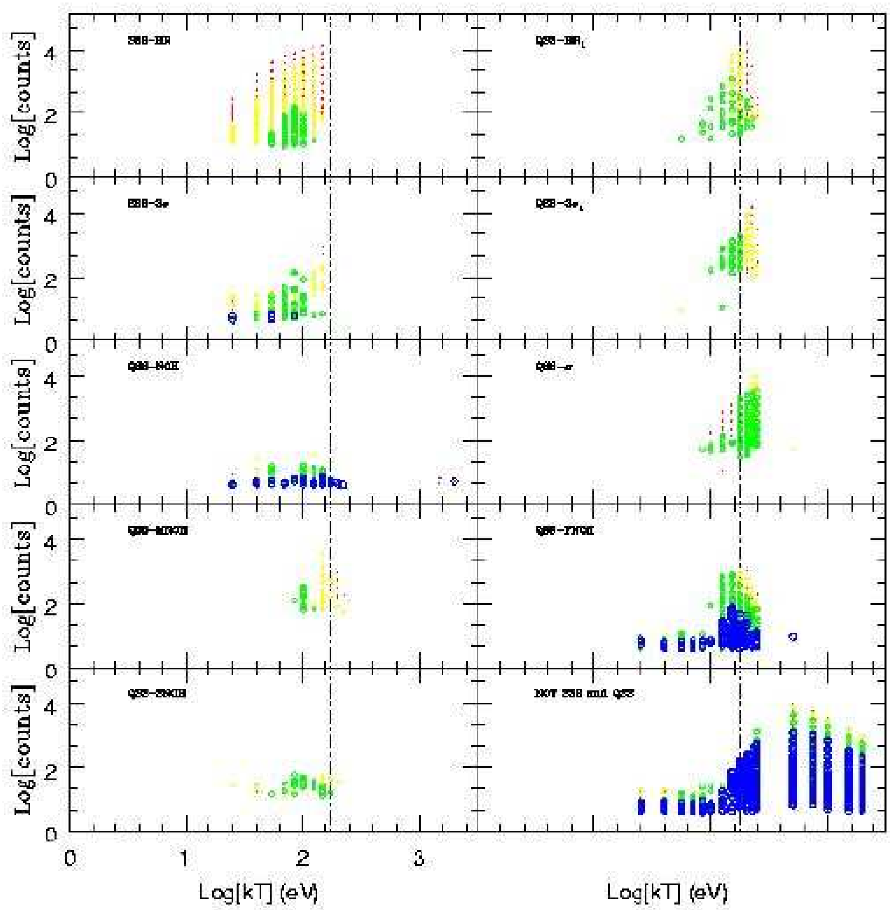

FIG. 4.— Test of the selection criteria as applied to thermal models. Along the vertical axis is the number of counts that PIMMS predicts would be detected for M31 sources (D = 780 kpc) with luminosities ranging from 10^{36} ergs s^{-1} to 10^{38} ergs s^{-1}. As described in §4, 4 values of N_H were considered: 4.0×10^{20} cm^{-2} (red points), 1.6×10^{21} (yellow; open circles) cm^{-2}, 6.4×10^{21} cm^{-2} (green; larger open circles), 2.5×10^{22} cm^{-2}(blue; largest open circles). The logarithm of the temperature is plotted along the horizontal axis. Points are shown only for those sources that would be identified as SSSs by the condition labeled in the box; the lower left panel shows sources that are not selected as SSSs and QSSs by any set of conditions.